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A Spatial Decision Support System for Livestock Production Planning and Environmental Management

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Abstract. *Spatial decision support systems are used to plan production systems and direct the implementation management strategies that are compatible with environmental protection goals. They enable resource managers to select appropriate production technologies that minimize environmental damage, and evaluate alternative management practices. This article describes a spatial decision support system (SDSS) developed to facilitate planning and management of environmentally sound livestock production. The SDSS integrates a geographic information system, spatial and biophysical modeling, and a knowledge-based system into an interactive tool to select suitable watershed land areas for siting livestock production, to select fields for manure application, and to determine the potential impacts of livestock production practices on groundwater quality.* ***Keywords.*** *Spatial decision support system, Livestock production, Environmental management, GIS.*

The livestock industry faces a number of challenging environmental and social issues, many of which are related to the number of animals in a production unit and fears over water quality. Central environmental issues include the role of animal manure in the contamination of groundwater by nitrates, the eutrophication of surface water by excess nitrogen and phosphorus applications, and the accumulation of heavy metals and pathogens in soils. Also, the polluting effect of ammonia volatization from manure and the contributions of nitrogen oxide and methane to global warming are receiving increased attention. Social issues include odor nuisances (Hamilton, 1992), animal welfare, and food safety.

During the last decade, the livestock industry in the United States has undergone considerable changes. The number of animals in a production unit has increased enormously, while the production system has become more concentrated and intense. With these changes, the following environmental quality issues have emerged. (1) For a given piece of land (e.g., a watershed constrained by landscape characteristics such as soils, land use and land cover, and topography) what type and size of livestock production can maintain the complimentary relationship between cropping systems and livestock? (2) Where can livestock units be located in the watershed to minimize potential pollution with odors and nutrients? (3) Where can livestock manure be applied in the watershed to minimize soil and water quality problems?

Answers to these questions require tools to: (1) Manage large volumes of spatially variable data. (2) Incorporate multiple objectives and competing criteria into the site delineation and planning process. (3) Estimate potential water quality impact of the livestock production system. (4) Present the results of the analysis in a variety of ways that enhance decision making.

This article describes a spatial decision support system (SDSS) to facilitate design and analysis of environmentally sound livestock production systems. It includes a brief overview of the SDSS and its various component and an example application that demonstrates the use of the system.

Methods and Material

SDSSs are tools that integrate spatial data and models with expert or knowledge-based systems to analyze semi-structured or ill-posed problems (Densham, 1991; Harsh, 1987; Armstrong et al., 1991). For planning the livestock production and environmental management, a SDSS evaluates alternative production practices to select those that are commensurate with environment protection goals. In the following section, details of a SDSS developed for livestock production planning are presented. Figure 1 shows the components of the SDSS developed in this study.

Geograph Information System (GIS)

A GIS can be broadly defined as "an information systems technology for collecting, storing, retrieving at will, transforming, and displaying spatial and nonspatial data from the real world" (Burrough, 1986). As a technology, a GIS has several components which can be used to perform the following tasks: (1) store, manage, and integrate large amounts of spatially referenced data; (2) enable spatial retrievals; (3) provide methods of analysis which relate specifically to the geographic

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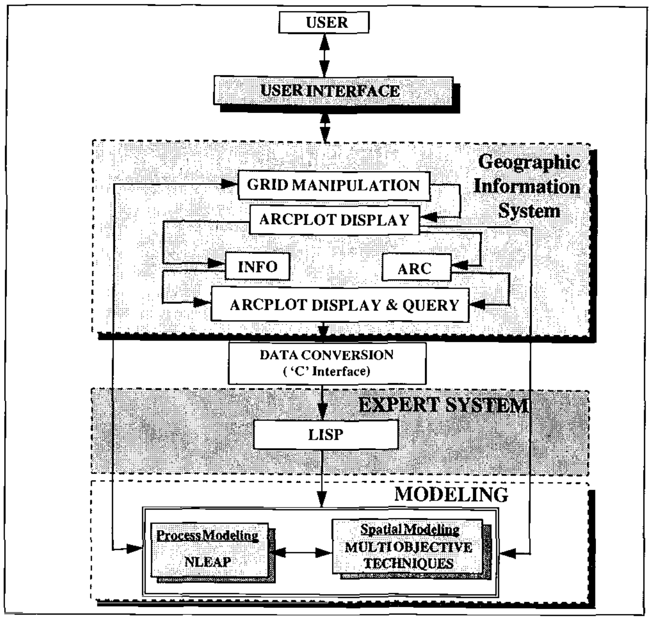

Figure 1–Architecture and conceptual framework of the SDSS.

component of the data; and (4) display the data or results of analyses in the form of maps, tables, or graphs. Given these functional components, it is not surprising that GIS has been widely used in fields such as natural resource conservation, environmental planning, forestry and agriculture, and transportation and utilities management, amongst many others (Antenucci et al., 1991).

A number of GIS software have been developed for spatial data management and modeling, the choice of which depends on the experience of the user and the nature of the application. In this study, the ARC/INFO GIS software (ESRI, 1992) developed and marketed by Environmental Systems Research Institute, was used to develop the SDSS. The ARC/INFO software can be envisioned as a collection of tools that operate on points, lines, and polygons, and performs data capture, error refinement and verification, coordinate transformation, database construction and manipulation, spatial analysis and modeling, and data query and display (Morehouse, 1992).

In ARC/INFO, the basic storage unit is the "coverage", which is a single layer of a map containing information about the spatial feature. Each coverage has a topology that defines the relationship between the spatial objects in the coverage. The topology allows performing operations such as contiguity analysis without accessing the spatial features' tables or coordinate. ARC/INFO also has a command sequencing and interpreting control language called arc macro language (AML), that permits structuring the command programs. AML provides string operations, loops, if-then-else blocks, and external file access protocols. Several program modules including ARCEDIT, ARCGRID, and ARCPLOT provide a wide range of functions, including data acquisition, spatial modeling, and interactive visualization and display of spatial data.

Modeling

Two modeling techniques were used in the SDSS—spatial modeling and biophysical modeling. Spatial modeling used multi-criteria evaluation technique (MCE) for: (1) determining optimal land areas for siting livestock production systems, and (2) delineating suitable areas for manure application. The second modeling technique involves the use of a biophysical model to evaluate the groundwater quality impacts of land application of manure, given the agricultural land use, type, and size of livestock production enterprises, and the amount of manure produced. Each modeling technique is briefly described below.

Spatial Modeling. The MCE technique, described in detail elsewhere (Carver, 1991; Jankowski and Richard, 1994), was incorporated with ARC/INFO GIS to determine suitable land areas for the planning of livestock production systems and for selecting suitable land areas for manure application. This technique is highly suited for this study because of its simplicity, its efficient treatment of multiple criteria and conflicting objectives, and its capability to

Table 1. Some criteria, factors, and factor scores used in the SDSS

(a) Criterion: Stream Proximity (m)

Factor	Score
Less than 50	0
50 - 100	2
100 - 200	6
200 - 300	8
300 - 400	9
Greater than 400	10

(b) Criterion: Soil Permeability (cm/h)

Factor	Score
Less than 0.15	0
0.15 - 0.51	2
0.51 - 1.52	4
1.52 - 5.10	6
5.10 - 15.2	8
Greater than 15.2	10

(c) Criterion: Road Proximity (m)

Factor	Score
Less than 50	0
50 - 100	2
100 - 200	6
200 - 300	8
300 - 400	9
Greater than 400	10

(d) Criterion: Slope (%)

Factor	Score
0 - 2	10
2 - 5	8
5 - 14	6
14 - 35	4
Greater than 35	0

(e) Criterion: Aspect (°)

Factor	Score
0 - 45	1
45 - 90	2
135 - 180	10
180 - 270	10
270 - 315	9
315 - 360	1

handle many different factors that may be involved in livestock production planning and decision making. In addition, the MCE technique can reflect the preferences of decision makers, and facilitates analysis of sensitivity of factors. Through analysis of sensitivity, the decision maker can either assess the validity of the factors used in ranking the various alternatives or examine inter- and intra-criteria preferences.

The MCE technique, as used here, involved two basic steps—formulating an effectiveness matrix of factor and factor scores for each physical landscape attribute, and assigning a weight vector of priorities reflecting the importance of each factor. Factors used in the analysis included: land slope, aspect, soil permeability, distance to roads, and proximity to stream, to mention a few. The suitability of land area i given a factor j was determined using the following equation:

$$S_{ij} = \sum_{i=1}^{N} f_{ij}\, w_j \qquad (1)$$

where
S_{ij} = suitability score
f_{ij} = effectiveness score
w_j = weight vector

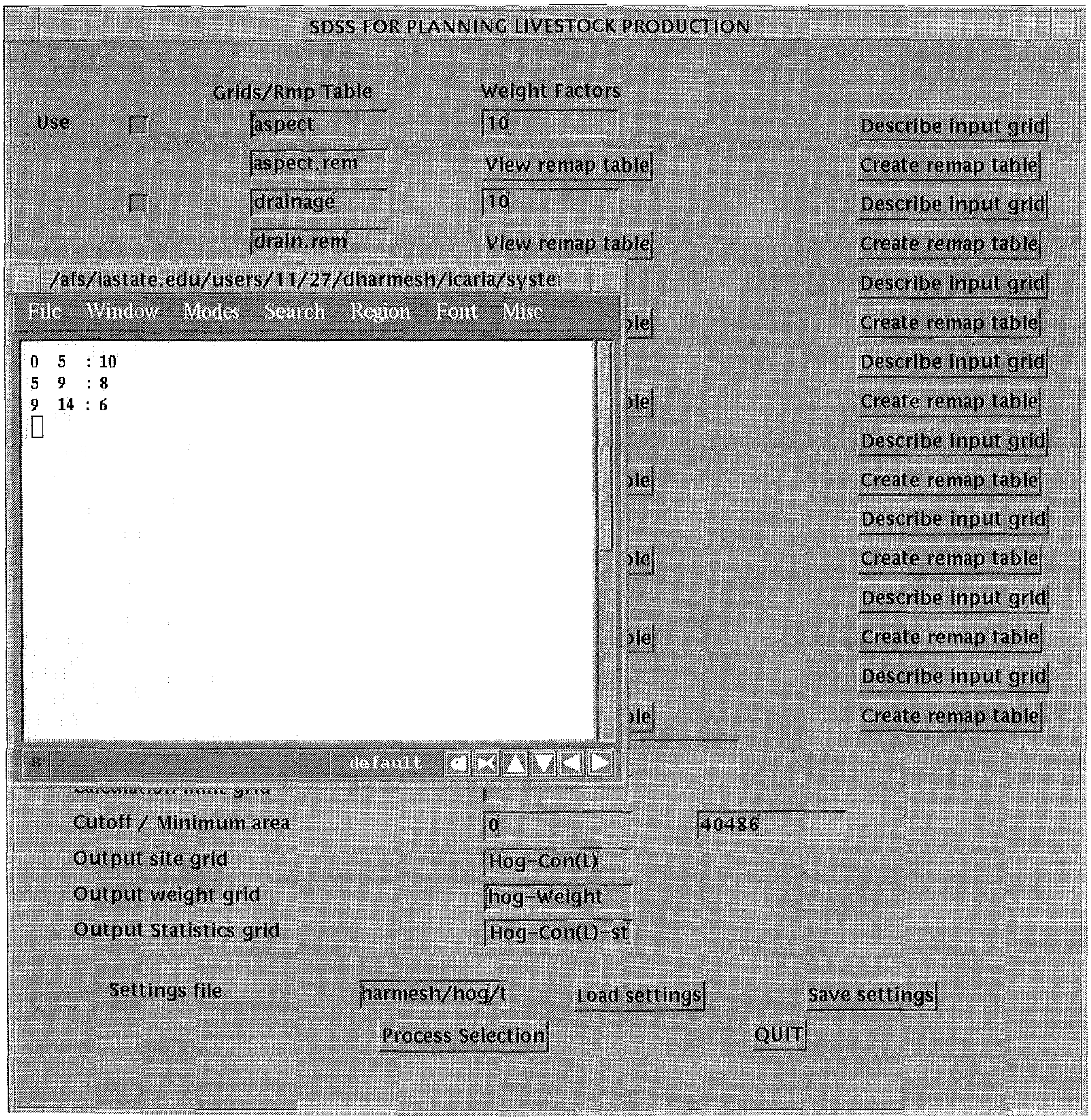

Figure 2–Major interaction screen for the SDSS.

The effectiveness score of a factor, f_{ij} (which may range from 1 to 10), and the corresponding weight of the factor, w_j (which may range from 0 to 100 with the total not to exceed 100) can take the following form:

$$w_j = (w_1, w_2, w_3, \ldots w_J) \quad (2a)$$

$$f_{ij} = \begin{bmatrix} f_{11} \cdots f_{1i} \\ \cdots\cdots\cdots \\ f_{1j} \cdots f_{ij} \end{bmatrix} \quad (2b)$$

In calculating S_{ij}, spatial modeling capabilities of the ARCGRID program module of ARC/INFO was used. The factors and factor scores used in the analysis are summarized in table 1. The scores assigned to each factor were obtained from an extensive review of the literature, together with information obtained from several state agencies and extension field offices. Implementing the MCE technique within ARC/INFO involved: (1) obtaining a composite suitability map by generating map coverages of the factors listed in table 1, (2) assigning factor scores f_{ij} by using a remap table, and (3) spatially organizing the factors and weights at the grid-cell level. Once the grid coverages had been assembled, a cumulative suitability grid was generated by using equation 1 and ARCGRID modeling tools. Several AMLs were written to facilitate calculation of the values in the cumulative suitability grid. These values were then rescaled to range from 0 to 100, with high values for high suitability and low values for low suitability. Rescaling was performed in ARCGRID with:

$$\text{Suitability grid} = \frac{\text{Suitability grid} \times 100}{\text{Max. value of Suitability grid}} \quad (3)$$

Biophysical Modeling. The potential impact of manure applications on groundwater quality was evaluated with the Nitrate Leaching and Economic Analysis Package (NLEAP) model. Details of the model can be found in Shaffer (1991). NLEAP was developed to accurately estimate nitrate leaching to groundwater beneath agricultural areas, determine nitrate leaching "hot-spots", and determine effectiveness of management strategies on farm-fields to reduce pollution of groundwater by nitrate. Originally, the model was developed for field-scale nitrate leaching assessment, but has recently been extended to the watershed-scale by using GIS (Shaffer and Wylie, 1993; Pierce et al., 1991).

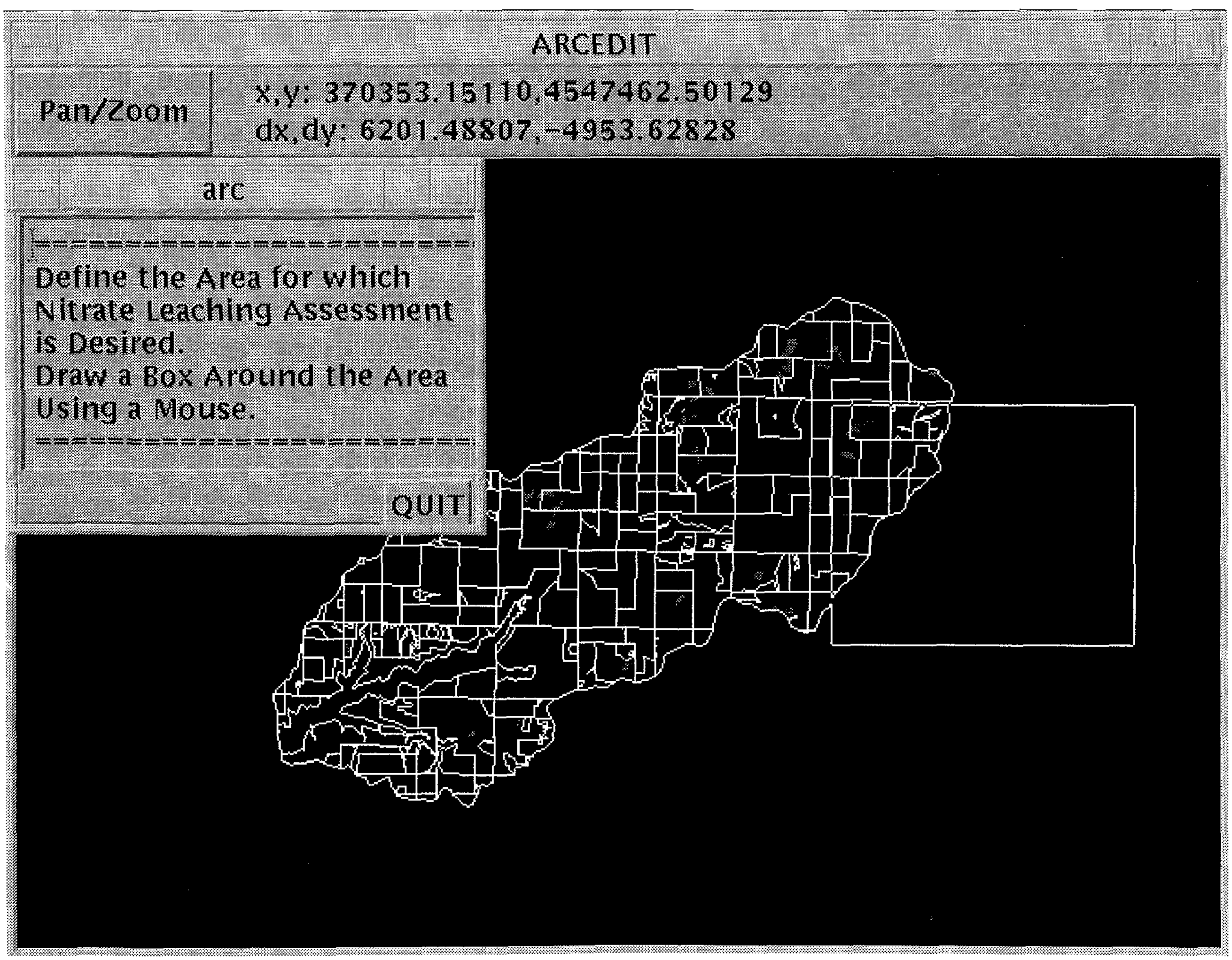

Figure 3–Sample interaction screen for defining areas for evaluating nitrate leaching potential.

Knowledge-based System

The use of knowledge-based systems or expert systems in agricultural management and environmental decision making has increased tremendously during the past decade. Plant and Stone (1991) described the various knowledge-based systems used in agriculture. Buick et al. (1992) described a knowledge-based crop rotation and production advisory system for developing farm-level management plans that meet yield targets, economic return goals, and environmental quality objectives. Lam and Swayne (1993) described RAISON, an expert system that integrates hydrological database, modeling, and GIS. Lanen and Wopereis (1992) evaluated optimal land areas for injecting manure slurry from intensive animal production. He et al. (1992) developed a knowledge-based system for site-specific fertilizer application.

The knowledge-based component of the SDSS discussed here was written in LISt Processing (LISP) language and was based on the Induction Dichotomy (specifically ID3) decision tree algorithm. Details of Induction Dichotomy were described by Quinlan (1986). In the SDSS, the knowledge base for nitrate leaching was developed by using simulations results from the NLEAP model for various combinations of climate, soils, and management practices. These results represented the training sets for inducing classification rules of nitrate leaching potential.

In developing the knowledge base using ID3 decision tree algorithm, an associational rather than positional representation was used. The primary difference between these representations has been discussed in detail in Quinlan (1986). Although associational representation requires more data storage, the input parameters (training sets) can be uniquely specified to facilitate user-initiated query. In building the decision tree, the user can specify the rules for choosing an attribute to use in partitioning the instances at the root node. These rules may include the choice of an attribute with the lowest or highest value, or a random selection of an attribute. In this study, the random selection of an attribute was kept as a default choice.

System Implementation

The SDSS was developed to run on a DEC workstation under the UNIX operating environment. However, with some modifications to the control files, it can be readily adapted to other workstations and microcomputers. The main design component of the system is a graphical user interface that lets the user interact with the modeling components through a mouse, and pop-up menus. Figure 2 shows the main interaction screen for the SDSS.

To demonstrate the SDSS, a visual trace of the screen display will be used to illustrate each stage of the user's progress through the system. In operating the SDSS, the

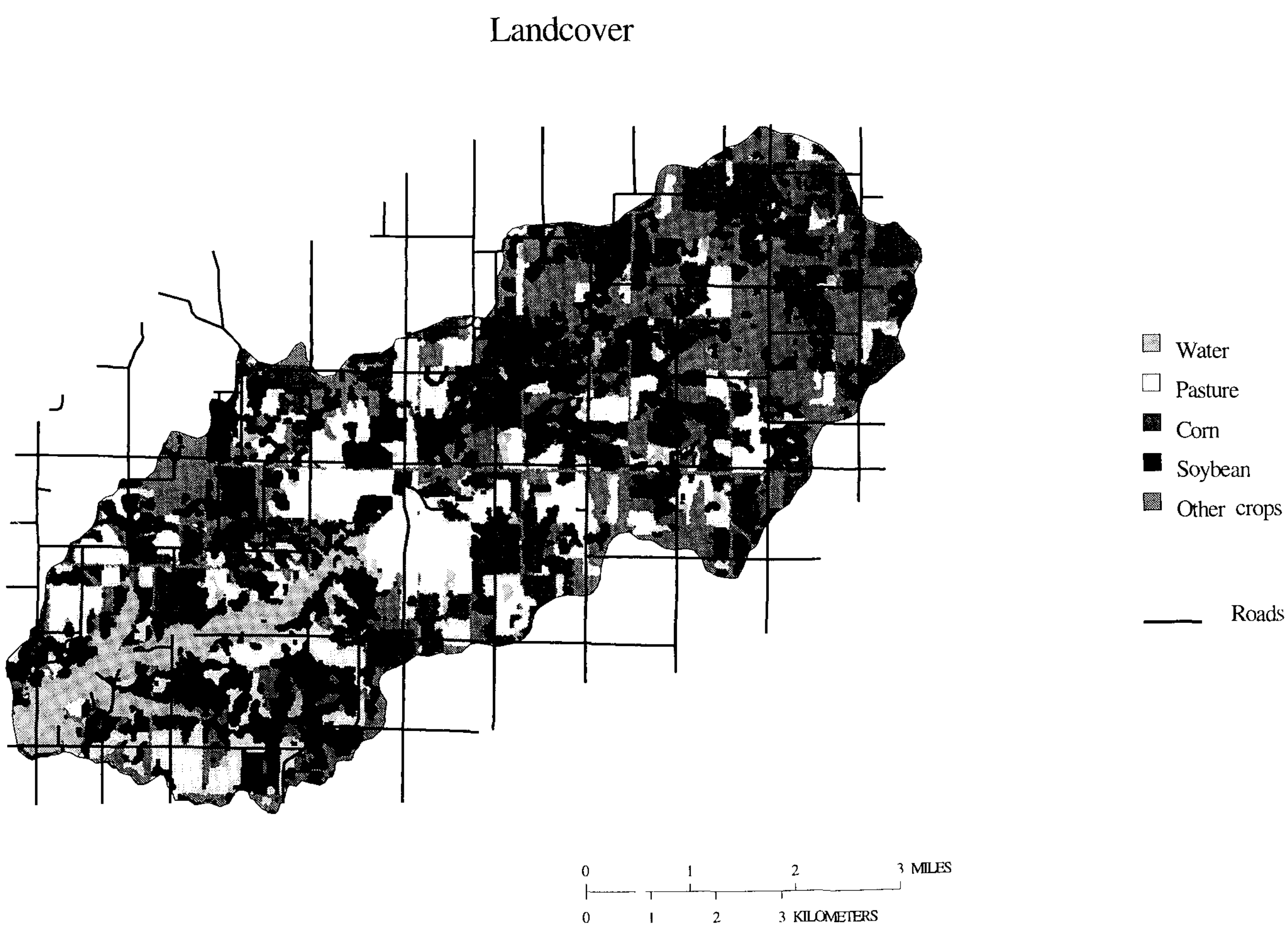

Figure 4–Distribution of land use in the Lake Icaria watershed.

user generates the various grid coverages for all the factors summarized in table 1 (e.g., aspect, land slope, soil drainage class, proximity to streams, etc.). The grid coverages can be generated by using the POLYGRID command in ARC/INFO or by generating a FISHNET grid that covers the entire study area. Then, the corresponding scores and weights are assigned to each factor grid coverage and criterion, respectively. Upon specifying the factor grid and weight grid coverages, the user begins spatial modeling in ARCGRID by selecting the "Process Selection" button (or icon). The system begins spatial modeling with the equations described earlier. The suitable land areas for each activity such as siting livestock units and manure application can be displayed in ARCPLOT or visualized in ARCVIEW version 2.0.

After delineation of suitable land areas the system prompts the user to define the region for which assessment of water quality impacts (e.g., nitrate leaching) is desired. This may be necessary if the objective of the user is to perform field-by-field assessment of nitrate leaching or to identify "hot-spots" of groundwater contamination. Using the mouse, the user can define this region by creating a "window" on the screen display (fig. 3) or by selecting the entire watershed. An interface program written in C language then converts spatial attributes of the selected region into the ID3 structured query format. After this, the user is prompted for additional information on fertilizer and manure application rates and tillage practices for the selected land areas.

Upon completion of all the inputs, the system interacts with the knowledge base to generate values of nitrate leaching potential. Here, the nitrate leaching rules induced from the NLEAP training sets and stored in the hierarchical format using ID3 decision tree algorithm, provide outputs of nitrate leaching for grid cells in the region defined. The computed values of nitrate leaching, expressed in terms of low, medium, and high leaching potentials can be analyzed and visualized within the GIS software package. The SDSS is uniquely structured such that whenever a factor score or weight is changed, the output screen is refreshed to reflect such a change.

Example Application

Description of Study Area

The SDSS described in this article was applied to the Lake Icaria watershed to delineate suitable land areas for planning small, medium, and large hog confinement units.

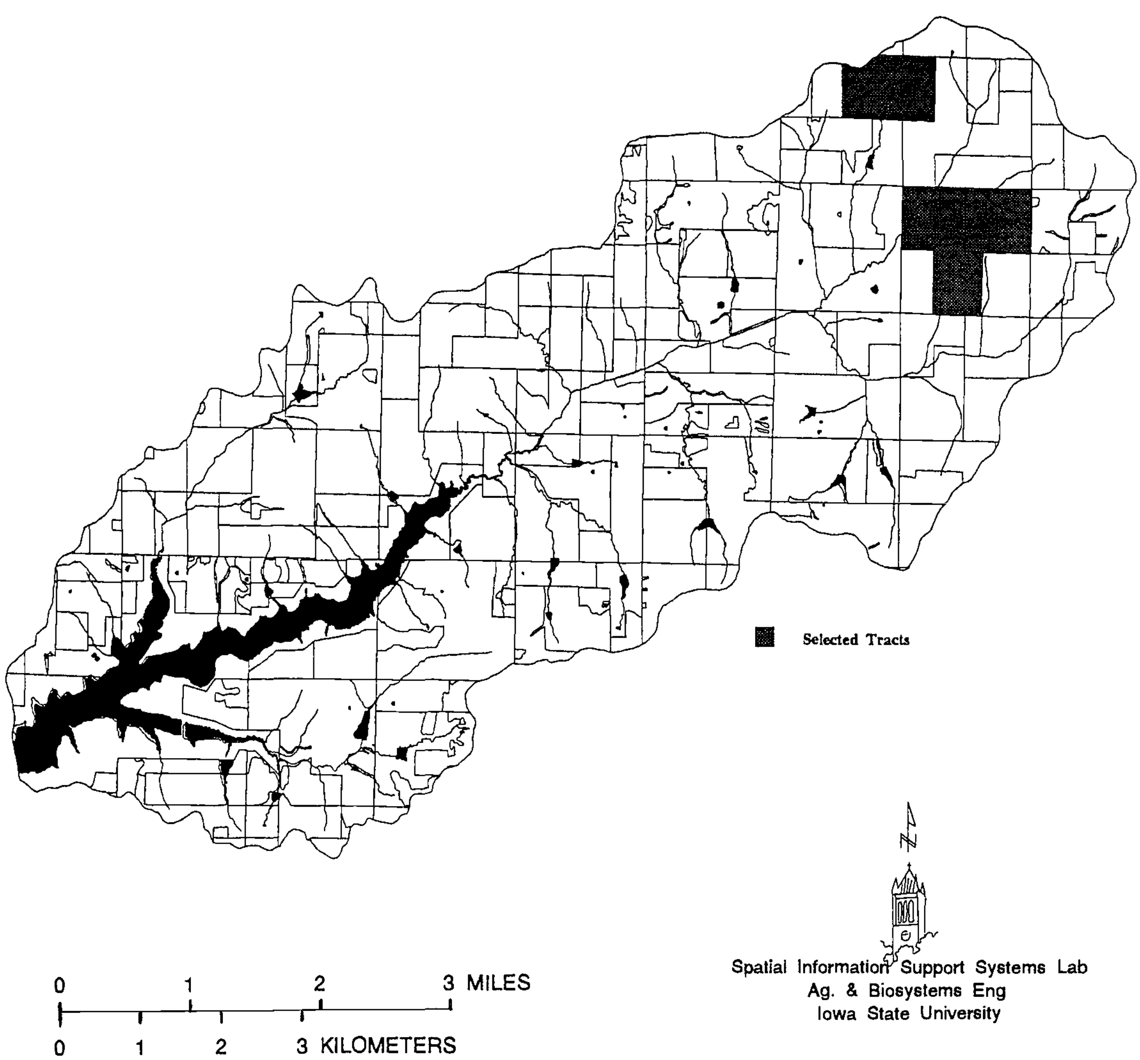

Figure 5–Spatial distribution of suitable land areas for siting large hog confinement units (suitable land areas aggregated at the tract level).

The 7075-ha Lake Icaria watershed is located in Adams County and is approximately 112 km southwest of Des Moines, Iowa. Topography of the watershed varies from gently sloping to moderately steep. Soils were developed primarily from loess, pre-Wisconsin till, or pre-Wisconsin till-derived paleosols. The predominant soil associations include: Sharpsburg-Adair (nearly level to moderately steep), Macksburg-Winterset (nearly level to gently sloping), and Shelby-Sharpsburg (moderately sloping to steep).

Land use in the Lake Icaria watershed consists primarily of row crops (corn and soybean) integrated with a few livestock production units. In 1991, about 49% of the watershed was under corn and soybean production, while 22.4% and 11.6% of the watershed, respectively, was under pasture and the conservation reserve program (fig. 4). About 12.5% of the watershed consisted of farmsteads, roads, parkland, and water. The remaining 4.5% of the watershed, which include irregular shaped tracts of land and parts of cropland fields that are nonfarmable, was idle land. Livestock production is a small, but important, component of the Lake Icaria watershed land use. A 1991 survey identified 580 cattle and several medium-size hog confinement operations in the watershed. The cattle herds are divided between 14 pasture operations distributed throughout the watershed. The hog confinement operations are located on the north side of the watershed.

Results of Example Application

A number of livestock production strategies were analyzed using the SDSS developed in this study. For brevity and to minimize repetition, only the results related to the implementation of large hog confinement systems (1,000 sows with 4-ha contiguous land area requirement) in the watershed are described in this article. A detailed description of results for other livestock production strategies that were evaluated using the SDSS can be found in a recent report (Leopold Center for Sustainable Agriculture, 1995).

For the Lake Icaria watershed, figure 5 shows the spatial distribution of the land areas suitable for siting large hog confinement units. In examining the result shown in figure 5, it is important to note that the suitable land areas were aggregated at the tract level. Nevertheless, for the 7075-ha Lake Icaria watershed, about 57 ha (or 0.8% of watershed area) was determined to be suitable for siting only two large hog confinement units. The land areas suitable for application of manure, as delineated by the SDSS, are shown in figure 6. Here, the suitable land areas, which total about 1277 ha (or 18% of watershed area), were aggregated at the grid cell level and this should be kept in mind when examining the results shown in figure 6. The cell size used in distributing watershed parameters was fixed at 100×100 m or 1 ha.

The groundwater quality impact of manure applied on the Lake Icaria watershed was evaluated. The two large

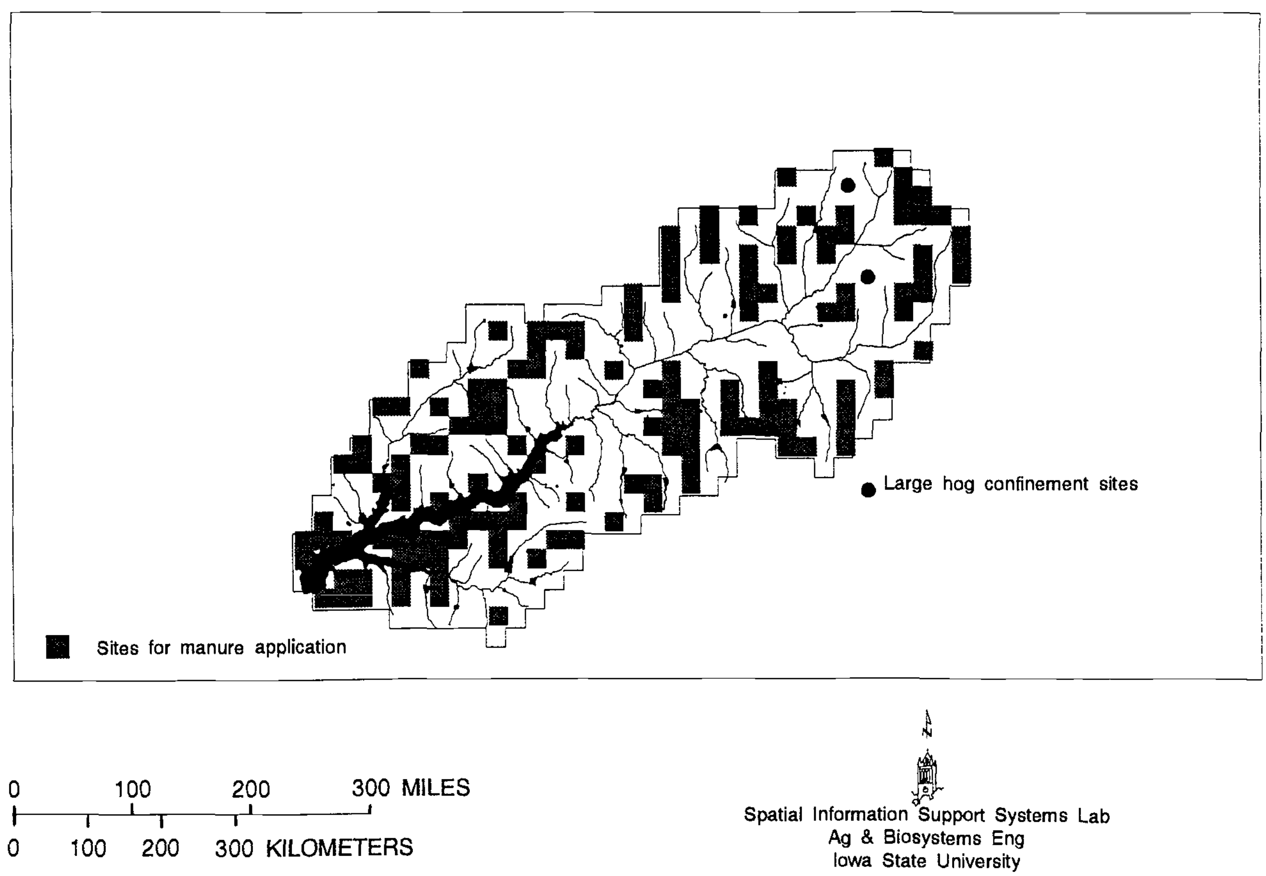

Figure 6–Spatial distribution of suitable land areas for manure application (suitable land areas aggregated at the tract level).

hog confinement units determined previously generate about 42.6 million liters of manure. When applied uniformly on the cropland areas of the watershed, this manure provides approximately 168 kg/ha of nitrogen. For a total nitrogen application rate of 207 kg/ha (based on yield goals), figure 7 shows the spatial distribution of nitrate leaching potential. Here again, the nitrate leaching losses, predicted by NLEAP and organized in the knowledge-based component of the SDSS, were aggregated at the grid cell level. Overall, the results obtained from this example application demonstrate the utility and potentials of the SDSS. The SDSS is being extended to include the socio-economic impacts of the livestock production system.

Summary and Conclusions

To address the environmental pollution problems associated with livestock production, local governments have passed new ordinances controlling the location of concentrated production systems, while the federal government has passed a number of environmental regulations. In addition, law suits seeking to reduce odor nuisances from livestock production are emerging. The general public is becoming more conscious of the impact livestock production can have on the quality of air, soil, and water. Livestock producers are under tremendous pressure to ensure that all forms of pollution from their production practices are controlled, or even eliminated. However, these pollution problems can only be minimized if resource managers, farm planners, and decision makers are equipped with decision support systems for planning environmentally sound production systems.

In this article a SDSS, developed by coupling ARC/INFO GIS, spatial and biophysical modeling, and knowledge-based system was described. The SDSS is uniquely structured to facilitate the planning and management of livestock production systems, and includes components for: (1) delineating suitable land areas for siting livestock production systems, given site-specific landscape characteristics, (2) determining suitable land areas for manure application, and (3) assessing the potential impact of manure application on groundwater quality. An example application to the Lake Icaria watershed showed the SDSS to hold great promise as an interactive and flexible tool for addressing some of the environmental problems associated with livestock production. Overall system also provides an integrated framework and user-friendly modeling environment for evaluating and comparing the attractiveness of several livestock production strategies. Finally, the evaluation of nitrate leaching potential, using the SDSS, provides decision makers with yet another useful tool for environmentally sound livestock production planning.

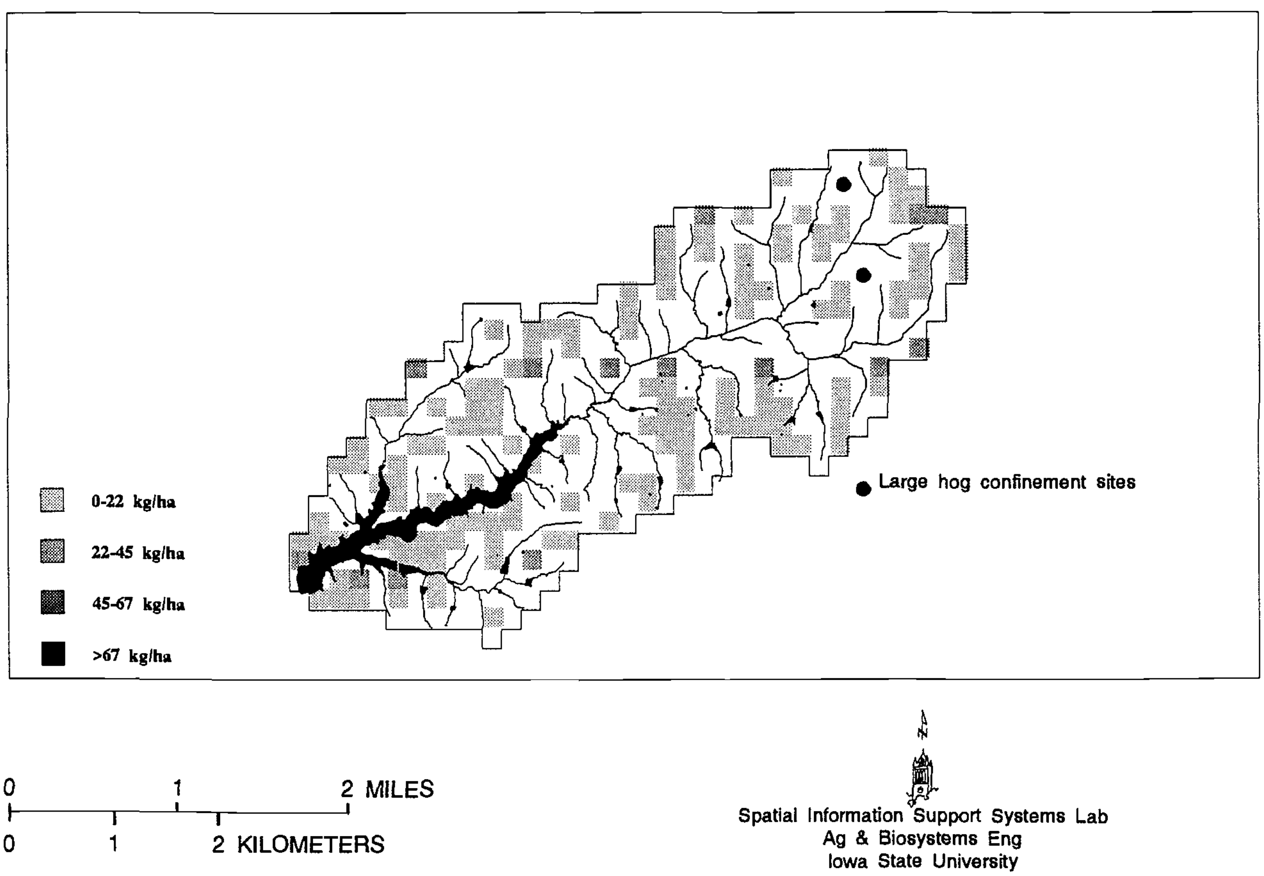

Figure 7–Spatial distribution of nitrate leaching potentials on manure-applied land areas (aggregated at the grid-cell level).

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